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Octupole Effects at Super and Normal Deformation

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Abstract. This presentation deals with recent results on the onset of octupole collectivity in superdeformed nuclei of the A $\sim$ 190 and A $\sim$ 150 regions as well as in actinide nuclei at normal deformation. It is shown that most of the properties of these negative parity sequences can be understood in terms of Random Phase Approximation (RPA) calculations, although the observations in some Pu isotopes continue to be a challenge to interpret.

Octupole correlations play an important, yet often subtle, role in the structure of many nuclei. These correlations usually manifest themselves through the presence at low excitation energy of states with odd spin and negative parity. The interest in octupole correlations comes, at least in part, from the fact that they are associated with the breaking of a symmetry of the nuclear Hamiltonian. In nuclei with a quadrupole deformed, axially symmetric shape, band structures of states with positive parity are the norm. They are associated with rotations where the shapes remain symmetric under space inversion. However, as soon as octupole degrees of freedom are involved, the potential becomes reflection asymmetric. Shell structure is responsible for the presence of octupole correlations as it is for many other nuclear phenomena. These correlations find their origin in long-range octupole-octupole interactions between nucleons. Microscopically, they can be described [1] as the result of the coupling between orbitals with $\Delta j = \Delta l = 3$, and they are especially strong when both protons *and* neutrons occupy orbitals near the Fermi surface fulfilling this condition.

A large fraction of Rick Casten's recent work as well as the vast majority of the presentations at this conference deal with low spin, positive parity excitations. In honor of Rick and as a salute to his many contributions to nuclear structure, it seemed appropriate, then, to broaden the scope somewhat by presenting some of the most recent results regarding octupole excitations and to cover both super and normal deformed nuclei.

In a number of nuclei, strong deformed shell effects are responsible for an excited minimum associated with a large, prolate deformation (major to minor axis ratio of about 2:1). In superdeformed (SD) nuclei of the mass A $\sim$ 150 region, there is much evidence for single particle behavior: observables such as the dynamic moments of inertia, $\Im^{(2)}$, the evolution of these moments with rotational frequency, and the measured quadrupole moments, Q_0, can in most cases be understood in terms of the occupation of specific single-particle orbitals [2, 3]. It was suggested in Ref. [4] that this behavior is a consequence of "extreme shell-model" behavior in which the SD nucleus is described by independent, non-interacting particles in a mean field.

In contrast, most excited bands in even-even SD nuclei of the A $\sim$ 190 region have

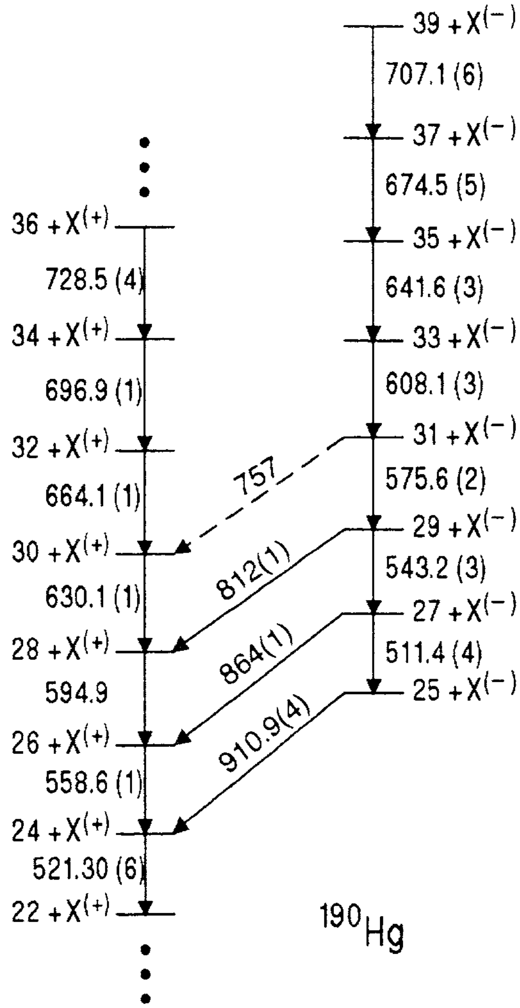

FIGURE 1. Partial level scheme of SD states in ^{190}Hg showing the E1 transitions linking SD band 2 to the yrast SD band. The uncertainties on the transition energies are given in parentheses. The X symbols reflect the fact that absolute spin values are not known at the present time.

been interpreted in terms of collective excitations. Specifically, evidence for octupole vibrations was first reported in the case of ^{190}Hg [5] where SD band 2 was found to deexcite into the yrast SD band instead of directly to levels in the normal deformed minimum, the usual decay path out of SD bands (see Figure 1). Band 2 was established to deexcite via E1 transitions [6] with rather low energy ($\sim$ 800 keV) and high transition rates (the corresponding B(E1) values are of the order of 10^{-3} *W.u.*) [7]. Similar evidence has also been reported for ^{194}Hg [8] and $^{196-198}$Pb [9]. The case of ^{194}Hg is particularly striking in that the absolute excitation energy as well as the quantum numbers of all the SD levels of interest have been established experimentally: this nucleus is one of only a handful where the transitions linking SD levels to states of normal deformation have been observed [8].

The SD minima in both the A $\sim$ 150 and A $\sim$ 190 regions are calculated [10, 11, 12] to be soft with respect to octupole deformation because of the presence of intruder orbitals ($j_{15/2}$ neutrons and $i_{13/2}$ protons) near the Fermi surface, where they are close to levels of opposite parity differing by three units ($\Delta l = 3$) in angular momentum ($g_{9/2}$ neutrons and $f_{7/2}$ protons). In fact, based on RPA calculations, Nakatsukasa *et al.* [13] proposed that most low excitations in A$\sim$190 even-even SD nuclei are associated with octupole vibrations. For example, both excited bands in ^{194}Hg have been associated with an octupole vibration over the entire frequency range where they are observed [8]; the same applies to SD bands 2 and 3 in ^{192}Hg [13], although in this case the bands are crossed by $j_{15/2}$ quasiparticle excitations at high spin. In ^{190}Hg, SD bands 2 (discussed above) and 4 are understood as being of octupole character, while band 3 is interpreted as a quasiparticle excitation [14].

Remarkably, while compelling evidence exists in the A $\sim$ 190 region, the situation is quite different near A $\sim$ 150. There is some evidence for inter-band transitions only for a single band in both ^{150}Gd and ^{152}Dy [15, 16]. In the latter nucleus, the first one where superdeformation was reported [17], five excited bands are known [16], and it is one of the weakest of those (band 6) that has been proposed to decay into the yrast SD band, i.e. the transitions of the yrast SD band were observed to be in coincidence with the γ rays of SD band 6, but the transitions linking the two bands were not observed. Nevertheless, based on this fragmentary evidence an interpretation in terms of an octupole vibration was proposed in Ref. [18]. A new Gammasphere experiment [19] has clarified the experimental situation regarding this band and has confirmed the interpretation in terms of an octupole excitation.

The large data set used recently to link the ^{152}Dy yrast SD band to the normal deformed levels [20] was also exploited to investigate the very weakly populated SD band 6. The relevant level scheme, given in Figure 2, indicates that 9 transitions with energies between 1645 and 1795 keV have been established to link SD band 6 to the yrast SD band. These transitions are of E1 character. Under the assumption that SD band 6 has the same transition quadrupole moment of 17.5 eb as the yrast SD band [21], the extracted transition rates (B(E1) $\sim$ 3-5 10^{-4} *W.u.*) are similar both to those observed among actinide nuclei exhibiting strong octupole collectivity in the normally deformed well [22] and to those of inter-band transitions in the SD wells of the A $\sim$ 190 nuclei [7] that have been interpreted in terms of an octupole vibration.

The RPA calculations by Nakatsukasa *et al.* [18] interpret SD band 6 as an octupole excitation with signature $\alpha = 1$. At zero frequency, the band is characterized by $K = 0$, but K-mixing is significant at the frequencies of interest because of the Coriolis force. In the work of Ref. [18] it was shown that the calculations reproduce the magnitude and evolution with frequency of the $\Im^{(2)}$ moment of inertia satisfactorily. The new data take such comparisons much further. Experiment and calculations are compared in Figure 3, where the Routhian of band 6 with respect to the yrast SD band is given as a function of the rotational frequency. The figure presents the lowest octupole excitation (dashed line), and the first 1p–1h configuration (solid line). From Figure 3, it is clear that the excitation energy and the evolution of the Routhian with frequency are well reproduced. Thus, these new results establish the first collective excitation in the SD well of an A $\sim$ 150 SD nucleus.

SD bands 2–5 are interpreted in terms of single neutron or proton excitations across the $N = 86$ and $Z = 66$ shell gaps [16, 18]. These bands are fed with intensities similar

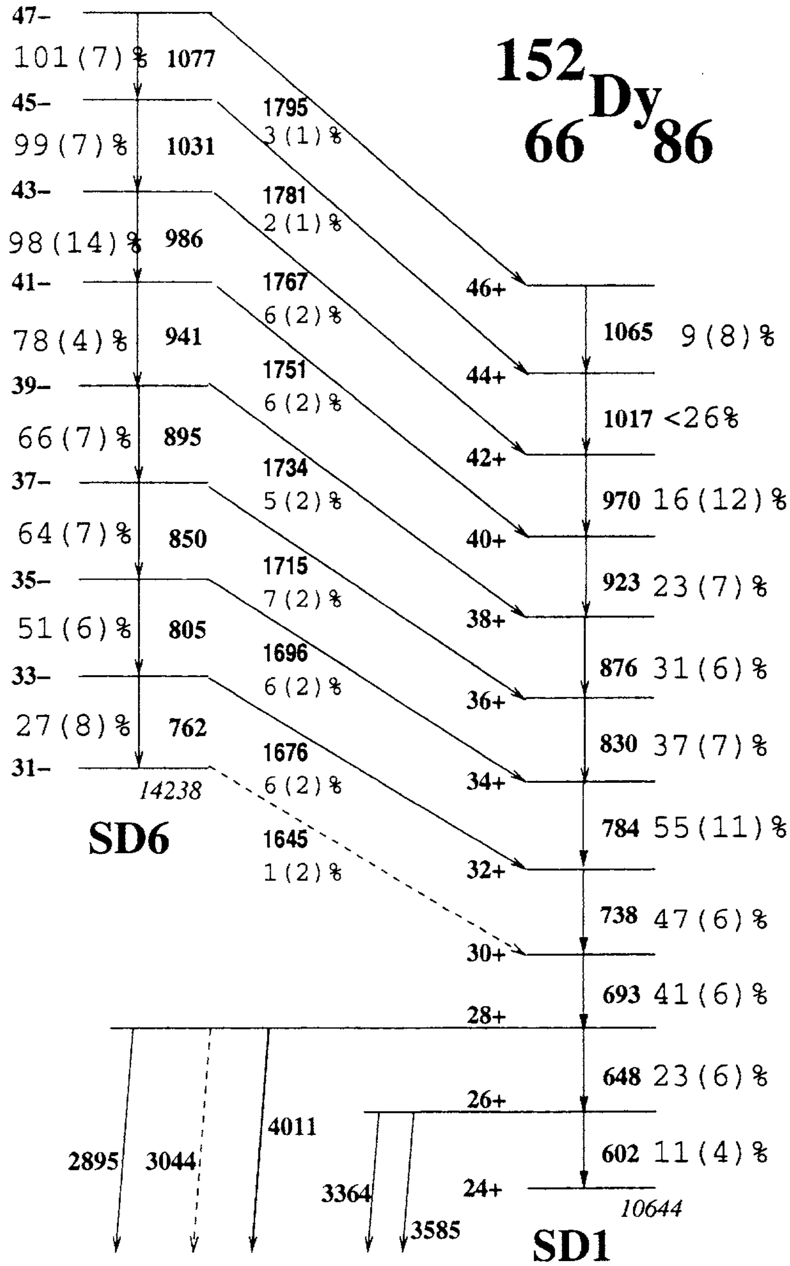

FIGURE 2. Partial level scheme of ^{152}Dy showing the lowest part of SD band 6, the lowest part of the yrast SD band 1 and the transitions that link the yrast SD band 1 to the normal states.

to that of band 6. Hence, their excitation energies with respect to the yrast SD band are likely of the same order as well in the frequency range where they are fed. Thus, the proton and neutron excitations of SD bands 2–5 are likely 1.6–1.8 MeV above the yrast SD band, and the present data also provide some measure of the SD shell gap at high frequencies.

The success of RPA calculations in reproducing the collective octupole excitations in the SD well is remarkable. However, at these large deformations, the density of states

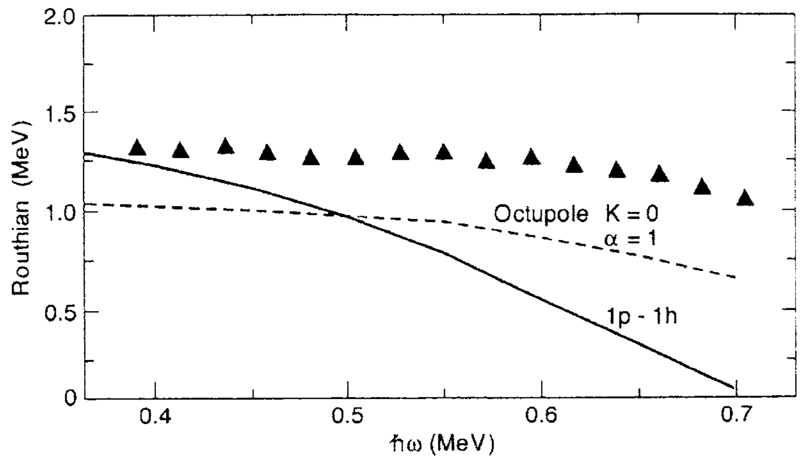

FIGURE 3. Routhians of band 6 with respect to band 1 as a function of rotational frequency in ^{152}Dy. The dashed line characterizes the lowest calculated SD excitation associated with a octupole vibration. The solid line likewise shows the lowest 1p-1h excitation which corresponds to SD band 2.

near the Fermi surface is somewhat smaller than it is at normal deformation. It is then worthwhile to investigate the predictive power of the calculations in this second regime. The nuclei of the actinide region seem particularly suited for such investigations since the orbitals located in the vicinity of their Fermi surfaces are the *same* as those found in the SD nuclei of the A$\sim$190 region. Here again, the RPA calculations have been quite successful in accounting for a good fraction of the available data. For example, the properties of negative parity states in ^{232}Th [23], ^{238}U [24], ^{244}Pu and ^{248}Cm [25] are reproduced satisfactorily. Yet, some surprises have been encountered in the lighter even-even Pu isotopes.

With Gammasphere at ATLAS, data on all Pu nuclei with mass A = 238-244, were obtained from measurements performed with Bi beams at energies $\sim$ 15% above the Coulomb barrier. This is the so-called "unsafe Coulomb Excitation" technique where the highest spin states are reached by taking advantage of both nuclear and electromagnetic processes. The measurements are described in Ref.[26]. Figure 4 compares the aligned spins i_x as a function of rotational frequency $\hbar\omega$ for the yrast sequences and the first negative parity cascades in $^{238-244}$Pu [26]. A number of interesting features clearly stand out: (i) all the Pu isotopes with mass A $\geq$ 241 exhibit a strong alignment in their respective yrast bands at $\hbar\omega$ $\sim$0.25 MeV, (ii) this alignment is not present at all up to the highest frequencies observed in ^{239}Pu and ^{240}Pu and is delayed at least up to $\hbar\omega$ $\geq$0.28 MeV in ^{238}Pu, (iii) the behavior of the alignment curve of ^{240}Pu is distinctly different from that of all the other even-even Pu isotopes, (iv) all negative parity excitations show the $\sim 3\hbar$ initial alignment, characteristic of the octupole phonon, and (v) an additional gain in alignment occurs at higher frequencies only in those isotopes where a drastic upbend occurs along the yrast line, while, in contrast, (vi) a reduction in relative alignment sets in between the two bands in ^{240}Pu. The sudden gains in i_x of 9-10$\hbar$ in the heavier Pu isotopes is consistent with the alignment under the stress of rotation of an $i_{13/2}$ proton [26]. All the available calculations (see [26] for details) indicate that the same strong proton alignment should occur around $\hbar\omega \sim 0.25$ MeV in the lighter Pu isotopes, yet it is not seen in ^{239,240}Pu and is delayed in ^{238}Pu. The effect is particularly striking in ^{240}Pu: only a small, smooth increase in alignment is observed over a range of 4-6 transitions beyond the point where the backbending occurs in the heavier Pu nuclei (Fig. 4).

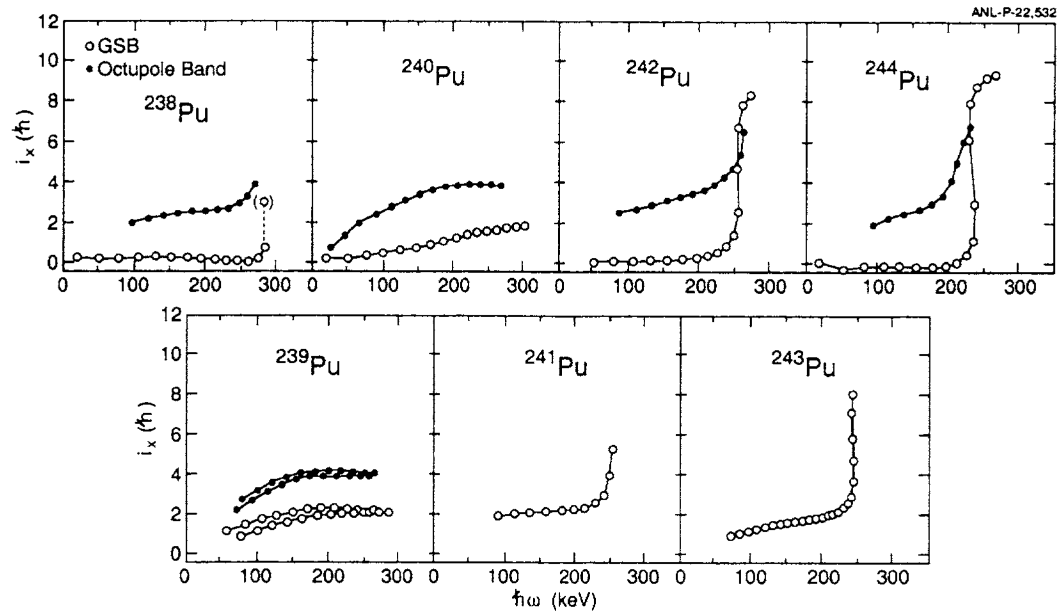

FIGURE 4. Aligned spins i_x of the yrast (open symbols) and octupole (filled symbols) rotational bands in the Pu isotopes.

In all the even-even Pu nuclei, the first excited band is of negative parity and is associated with an octupole vibration. This observation, together with the fact that octupole correlations are known to significantly alter alignment patterns seen in reflection asymmetric nuclei [27], makes it worthwhile to consider additional indications for stronger octupole correlations near A=240. In Ref. [26] it is shown that only in $^{238-240}$Pu the states of the yrast band become interleaved at high spin with the levels of negative parity to the extent that they essentially form a single band like in ^{222}Th and ^{229}Ra [28], two of the best examples of nuclei with static octupole deformation. Also, in ^{239}Pu, levels with the same spin but opposite parity are located close in energy: the $49/2^+$ and the $49/2^-$ levels are 17 keV apart, the two 53/2 states are separated by only 8 keV and the 57/2 levels are within 26 keV. Hence, these states form so-called parity doublets, as would be expected for odd nuclei with octupole deformation. Thus, it appears that, at least from the point of view of the level energies, the three lightest Pu isotopes behave like octupole deformed rotors at the highest spins. Additional evidence is provided by the measured ratios of the reduced E1 and E2 transition rates: the values of the induced intrinsic dipole moment D_0 deduced from such data become quite large at high spin only in $^{238-240}$Pu. For example, $D_0 \sim 0.2$ fm for I$\geq 21\hbar$ in ^{240}Pu [26], a value of the same order as those observed in light Th nuclei, which are among the best examples of octupole deformed nuclei. Finally, as discussed recently by Sheline and Riley [29], the hindrance factors for alpha decay in the light Pu isotopes are smaller than those seen in all neighboring nuclei and are of the same order as the values measured in the octupole deformed Ra, Rn and Th nuclei. In addition, in ^{240}Pu strong El transitions linking members of the second-excited 0^+ band to the negative parity band have also been observed [30]: the measured B(El)/B(E2) ratios are of the same order as those measured for the octupole band itself. The nature of this second-excited 0^+ band is presently not understood, but the presence of strong E1 transitions can again be viewed as illustrating the importance of octupole effects in ^{240}Pu.

The experimental evidence suggests that a transition from an octupole vibration to stable octupole deformation may have occurred. Such an evolution with angular momentum has been predicted in Ref. [31]. Detailed microscopic calculations are needed to fully account for the enhanced importance of octupole correlations near ^{240}Pu. In particular, the role of the octupole-driving orbitals needs to be fully explored. In this context, it is striking that in the immediate odd-even neighbors of ^{240}Pu the $\Delta l = 3$, $\Delta\Omega = 0$ particle-hole configurations $\pi\{3/2^-[521]3/2^+[651]^{-1}\}$ and $\nu\{7/2^+[624]7/2^-[743]^{-1}\}$ come close in energy to the Fermi surface (within 0.5 MeV) and are expected to play a role in the ground state configuration.

To summarize, this presentation has focused on recent studies of octupole effects in normal deformed and superdeformed nuclei. In particular, the first case of an octupole excitation in the A $\sim$ 150 SD region has been discovered in ^{152}Dy. The absolute excitation energy of the lowest level in the octupole SD band has been measured to be 14238 keV. In other words, the octupole excitation is located at an $\sim$1.3 MeV excitation energy above the SD ground state. Octupole collectivity in the SD nuclei appears to be well described by RPA calculations. While such calculations are also quite successful in actinide nuclei, the strength of the octupole correlations near ^{240}Pu appears to be such that, at the highest spins, $^{238-240}$Pu exhibit properties associated with stable octupole deformation, suggesting that a transition with spin from a vibration to stable deformation may have occurred.

The author presents Rick Casten his most heartfelt wishes for the continuation of his stellar scientific career. May his life also remain one joyous adventure. He thanks the organizers of this conference for the opportunity to present these data. Thanks are also due to his many colleagues who have contributed to the results presented in this contribution. They are too numerous to be all listed here. Special recognition is due to his colleagues at ANL, K. Abu-Saleem, I. Ahmad, M.P. Carpenter, T. L. Khoo, F.G. Kondev, T. Lauritsen, C. J. Lister, and I. Wiedenhoever (presently at Florida State University), without whom none of this work would have been possible.

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